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This information is being published in preliminary form in order to expedite its early release.

ABSTRACT

A programmer to automate the SNAP-8 mercury-loop startup started the system from an initial condition in which all system pumps were powered by an auxiliary power source at reduced frequency and in which there was no mercury in the mercury pump. The final condition at the end of startup was self-sustaining operation of mercury loop and all pumps were powered by the turbine-alternator at rated frequency. The programmer was successfully used for 26 mercury-loop startups.

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SUMMARY

An experimental automatic startup sequencing programmer for the SNAP-8 space power system was designed, assembled and tested. The programmer operated from an initial condition in which all system pumps operated on auxiliary power at reduced frequency and the mercury pump contained no mercury. The final condition of the programmed startup was self-sustaining operation of the mercury loop (flow, 6600 lb/hr), and all pumps were powered by the turbine-alternator at rated frequency (400 hertz). The programmer was successfully used for 26 mercury-loop startups.

INTRODUCTION

As part of the development of the SNAP-8 space power system (ref. 1), an investigation of system startup characteristics was conducted using the SNAP-8 ground test facility at the Lewis Research Center. These startup tests were mainly concerned with evaluation of the effects of specific system operating variables on the character of the startup transient and component interactions. Bringing the mercury loop to self-sustaining operation with a mercury flow rate of 6600 pounds per hour is the most critical portion of SNAP-8 startup. A description of the startup sequence and some of the results of these startup tests are presented in references 2 and 3.

The mercury loop startup sequence was performed manually during the initial stage of the test program in order to gain basic information required for the design of the sequencing logic of an automatic startup programmer since a flight system would, in most applications, be required to start by remote command. For these reasons a breadboard startup programmer was designed and fabricated at the Lewis Research Center. The design of this programmer and its performance during 26 startups of the mercury loop are discussed herein.

SYSTEM DESCRIPTION

The various valves of the SNAP-8 test system, controlled by the start programmer, are shown in figure 1. The loop of prime interest is the mercury loop. This loop includes four major SNAP-8 components: the mercury pump, the boiler, the turbine-alternator and the condenser. The standpipe shown in the figure is used to control the mercury inventory in the loop. Mercury can either be added to or withdrawn from the loop by variation of the cover gas pressure in the standpipe. During the startup a fixed gas pressure is maintained on the standpipe. Valve V217 is used to isolate the standpipe from the mercury loop.

The portion of the lubricant-coolant loop shown in figure 1 is used to provide bearing lubrication and cooling for both the turbine-alternator and the mercury pump. Redundant valves are used at the inlet and outlet of each component. Lift-off seals on both the turbine-alternator and mercury pump provide a seal between the mercury and lubricant-coolant fluids when either component is operating below the speed at which the viscous seals are effective. The lift-off seals are lifted for normal operation by pressurizing the bellows attached to the seals. Valves V417 and V434 provide the necessary pressure to lift these seals.

Also shown in figure 1 is the NaK-to-NaK auxiliary start heat exchanger that transfers heat from the primary loop, during reactor startup, to the heat-rejection loop prior to the mercury loop startups. Valve V117 is used to shut off the auxiliary start loop flow during the startup sequence.

Two pressure transducers and one weight transducer were used to sense the condenser inlet pressure, the mercury pump inlet pressure, and the standpipe mercury inventory.

All of the valves shown in figure 1 were operated in an on-off mode with the exception of the mercury flow control valve, V230. This valve was an electro-hydraulically operated valve controlled by an analog computer.

START-PROGRAMMER DESIGN

The programmer operated from an initial condition in which all system pumps are operating on an auxiliary power source at rated frequency and the mercury pump contains no mercury. The final condition of the programmed startup is a self-sustaining operation of the mercury loop (flow rate, 6600 lb/hr) and all system pumps are powered by the turbine-alternator at rated frequency (400 hertz). Prior to the mercury-loop startup, the primary NaK loop and heat rejection loop were slowly brought up to operating temperature and the lubricant-coolant loop was operating. The functions of the start programmer are shown in the block diagram of figure 2. Details of the design are presented in the following discussion.

Automatic-Manual Valve Operation

Several valves (V117, V210, V217, V247, and V260) had to have provision for either manual operation or automatic operation by the start programmer. An automatic-manual mode switch was therefore provided for each of these valves on the start programmer panel.

To avoid cycling these valves when switching between the manual and automatic modes, two design features were incorporated in the programmer. First, a panel light was provided for each of these valves to indicate the position the valve would seek when operating in the automatic mode. These lights in conjunction with the valve position lights provide a visual indication of proper operation of the valve control circuits. Secondly, a make-before-break relay was used to switch the valves between manual and automatic modes of operation. Thus, the only precaution to be taken when switching the valves between automatic and manual modes is to check the position of the manual switch when switching to manual mode, or the indication light on the start programmer panel when switching to automatic mode.

Standpipe Operation

During the mercury loop startup sequence the mercury standpipe valve, V217 (fig. 1), was initially open, allowing mercury to flow from the standpipe into the mercury loop. When the standpipe valve was operated in the automatic mode, it was energized to the closed position by the adjustable meter relay that provided the readout for the weight sensor on the standpipe. Thus, the desired mercury loop inventory was automatically obtained by setting the trip point on the standpipe meter relay to be the difference between the initial standpipe weight and the desired weight of mercury to be transferred from the standpipe to the mercury loop. Once the standpipe valve, V217, was closed, the automatic control circuit is electrically sealed-in and requires manual reset.

Mercury Pump Inlet Pressure Permissive

Opening the mercury pump inlet valve, V207 (fig. 1), initiates the mercury loop startup. To insure that mercury has reached the mercury pump, a pump inlet pressure requirement was used as a permissive signal to continue the startup sequence. An adjustable meter relay, used as the readout for the mercury pump inlet pressure transducer, was used to accomplish this function. When this meter relay was tripped the following occurs: valves V247, V206, and V260, between the mercury pump outlet and the boiler, were opened. Valve V117 is closed, shutting off the auxiliary start loop flow to the heat rejection loop. An adjustable time delay relay was also activated, to allow any transients produced by the above operations to settle before proceeding with the start sequence.

When the meter relay circuit tripped it was electrically sealed in, since the mercury pump inlet pressure will later drop below the trip value.

Mercury Flow Control Valve Operation

The purpose of the flow control valve, V230 (fig. 1), was to provide a programmed mercury flow ramp to the boiler and to set the steady-state flow in the mercury loop. An analog computer, with a flow feedback signal, was used to program this hydraulic valve. The start programmer supplied two signals to the analog computer for the control of this valve. The first signal was supplied by the time delay relay activated by the mercury pump inlet pressure meter relay. This signal opens the flow control valve slightly and also activates another time delay relay. The initial opening of the valve permits a very small flow to pass through the liquid venturi (fig. 1), producing a flow feedback signal for the computer. When the second time delay relay times out, allowing sufficient time for the flow feedback signal to be established, a second signal is sent to the computer to initiate the mercury flow ramp.

Condenser-Outlet Valve Operation

The condenser-outlet valve, V210 (fig. 1), can be automatically opened by either: (1) the end of the mercury flow ramp, or (2) a specified condenser inlet pressure. In the first mode the valve was opened by a signal from a time delay relay that was activated at the start of the mercury flow ramp and preset for the length of the flow ramp. In the second mode the valve was opened by a signal from the adjustable set point meter-relay that provides the readout for the condenser inlet pressure transducer. Once the selected mode opened the valve, the valve control circuit, in the automatic mode, was electrically sealed in and had to be reset manually.

Frequency Dependent Functions

Shortly after the beginning of the mercury flow ramp the turbine-alternator started to accelerate. During this acceleration the start programmer performed two functions, each at a different frequency. These functions were: (1) transferring the four system pumps from an auxiliary power supply to the output of the accelerating turbine-alternator at a specified frequency (pump bootstrapping frequency), and (2) opening the lubricant-coolant valves and pressurizing the lift-off seals on both the turbine-alternator and the mercury pump. A separate series-tuned inductance-capacitance (LC) circuit was used to trigger a silicon control rectifier and relay in order to perform each of the above two functions. Since the test program required that a range of bootstrapping frequencies be investigated (220 to 300 hertz), a capacitive decade box was used instead of a fixed capacitor in the appropriate series-tuned LC circuit. This permitted the pump bootstrapping circuit to be conveniently retuned for each bootstrap frequency. Three-pole, double-throw contactors were used to transfer each pump from the auxiliary power source to the alternator. By using a separate contactor on each pump, any or all pumps could be transferred at the bootstrap frequency. Once the transfer circuit was activated, it was electrically sealed in and required manual reset. To transfer the pumps from the alternator to the auxiliary power source, the frequency sensing circuit was first switched off and the pumps will then transfer when the manual reset is activated.

Preliminary Programmer Adjustments

Prior to switching the various functions of the start programmer to the automatic mode, several preliminary adjustments were required. The meter relays used for the standpipe weight, the mercury pump inlet pressure, and the condenser inlet pressure (if used to open valve V210) were set to the required values. The three time-delay relays used in the start programmer were adjusted for the proper time settings. These time settings were: (1) the time delay between the mercury pump inlet pressure trip and the slight opening of valve V230; (2) the time delay between the slight opening of valve V230 and the start of the mercury flow ramp; and (3) the time-duration of the mercury flow ramp (if this logic is used to open valve V210). In addition, the proper capacitance valve for the pump bootstrapping tuned circuit was also selected.

With control power on, all reset circuits were manually activated. Proper operation of the start programmer was confirmed by checking the valve indicator lights on the start programmer panel. All start programmer functions were manually switched to the automatic mode.

At this point in the procedure all the valves operated by the start programmer (fig. 1) were in the closed position, except for the standpipe valve, V217, and valve V117, that controlled the auxiliary start loop flow. All system pumps, except the mercury pump (which was inoperative) were operating on a facility power source at the bootstrap frequency. Immediately prior to activating the start programmer sequence, the mercury pump was started and operated at the bootstrap frequency. The lift-off seals were kept in contact with the pump shaft, and the lubricant-coolant valves were in the closed position.

DISCUSSION OF RESULTS

The functioning of the start programmer may be followed by referring to the experimental data for a typical start sequence presented in figure 3. For this start sequence the duration of the mercury flow ramp from 0 to 6600 lb/hr was approximately 85 seconds, while the bootstrap frequency (switch over from auxiliary power to turbine-alternator power) was 240 hertz.

Once the mercury pump had been started (fig. 3d), the start sequence was initiated by opening valve V207. This action permitted the mercury in the standpipe to fill the dry mercury pump cavity. The somewhat rapid decrease in standpipe weight, as shown in figure 3f, gives evidence of this filling action. Once the pump was filled, the pump inlet pressure increased very rapidly, as shown in figure 3a. When the pump inlet pressure reached 30 psia, the start programmer closed valve V117, reducing the auxiliary start loop flow to zero (fig. 3c) and opened valves V247, V206, and V260. A 10- to 15-second time delay was provided before the next step in the start sequence to allow any perturbations caused by opening valves V247, V206, and V260 to settle out.

At the end of the time delay, the flow control valve (V230) was opened very slightly. The ensuing small flow through the liquid venturi (fig. 1) provided a flow feedback signal for the programmed mercury flow ramp. The 30-second time delay between the slight opening of the flow control valve (V230) and the start of the mercury flow ramp provided sufficient time for the flow feedback signal to be established. Shortly after the flow ramp had started (fig. 3b) the turbine-alternator began to accelerate as shown by the alternator frequency trace in figure 3e. When the accelerating alternator reached the bootstrap frequency (240 hertz in this case), the four system pumps were transferred to the alternator and then accelerated to 400 hertz with the alternator. The pump transfer is verified by the increase in the mercury pump speed (fig. 3d) and the change in the acceleration rate of the alternator due to the pump load as shown in figure 3e.

Between the time that the pumps were transferred from auxiliary to turbine-alternator power and 400 hertz operation was reached, the lubricant-coolant valves on the mercury pump and alternator were opened and the lift-off seals actuated.

For the startup example given, the condenser outlet valve (V210) was opened by the signal indicating the end of the mercury flow ramp, rather than by the condenser inlet pressure signal. The opening of the condenser outlet valve (V210) can be verified by noting the time at which the mercury flow ramp ended (approximately 165 seconds on figure 3b) and then referring to the mercury pump inlet pressure trace, figure 3a, for the same time. The resulting jump in the pump inlet pressure was due to the condenser outlet valve opening upstream of the pump inlet.

The final start programmer operation that occurred in this start sequence was the closing of the standpipe valve, V217, when the programmed mercury inventory had been reached in the mercury loop. The valve closure occurred at approximately 180 seconds (on figure 3f), and the standpipe weight remained constant after this time. Two factors that determine how long it takes for the mercury to be transferred from the standpipe to the mercury loop are the amount of mercury to be transferred and the pressure maintained on the standpipe. With the programmer sequence complete, the mercury loop was operating at a 6600 lb/hr self-sustaining flow condition, and all four system pumps were receiving power from the alternator at 400 hertz.

This automatically programmed startup sequence was used for 26 startups during the test program. Experimental data obtained from these tests, as typified by figure 3, show that the control logic used in the start programmer was compatible with the SNAP-8 system and could be adapted to a flight version of the SNAP-8 system start programmer. The data, when compared with data from previous manual startup tests, show that the automatically attained test conditions were more accurate and more repeatable.

CONCLUDING REMARKS

A start programmer was designed and built to be used in the SNAP-8 startup test program conducted at the Lewis Research Center. The programmer operated from an initial condition in which pumps were driven by power at reduced frequency and the mercury pump contained no mercury. The final condition at the end of startup was self-sustaining operation of the mercury loop (flow rate 6600 lb/hr) and all pumps were powered by the turbine-alternator at rated frequency (400 hertz).

The start programmer was used successfully for 26 automatic system starts during the test program. The experimental data from these startup tests show that the system startup was accomplished successfully, accurately, and with excellent reproducibility. Similar logic could be adapted to a flight version of the SNAP-8 system start programmer.

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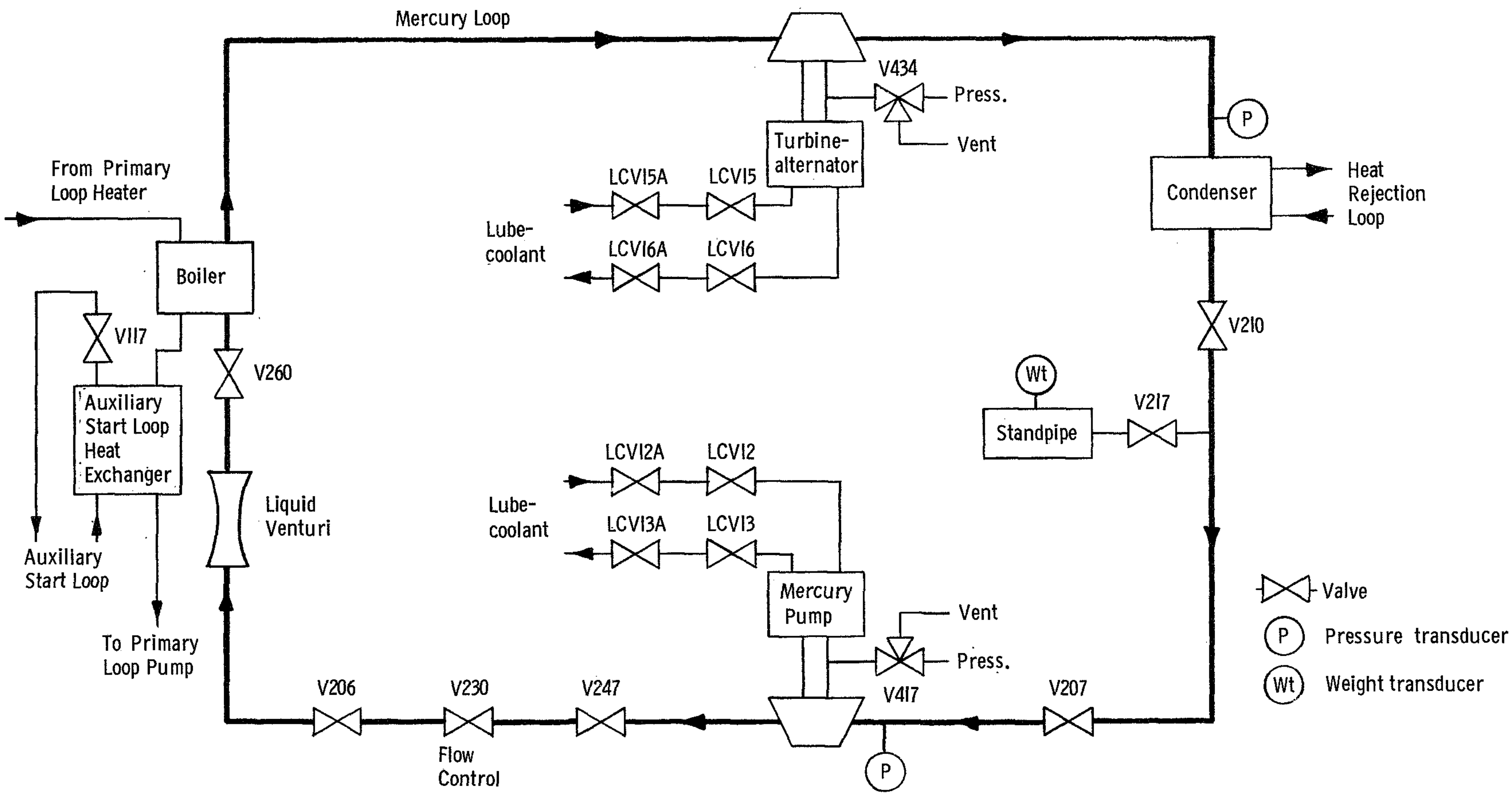

Figure I. -Valves controlled by the programmer.

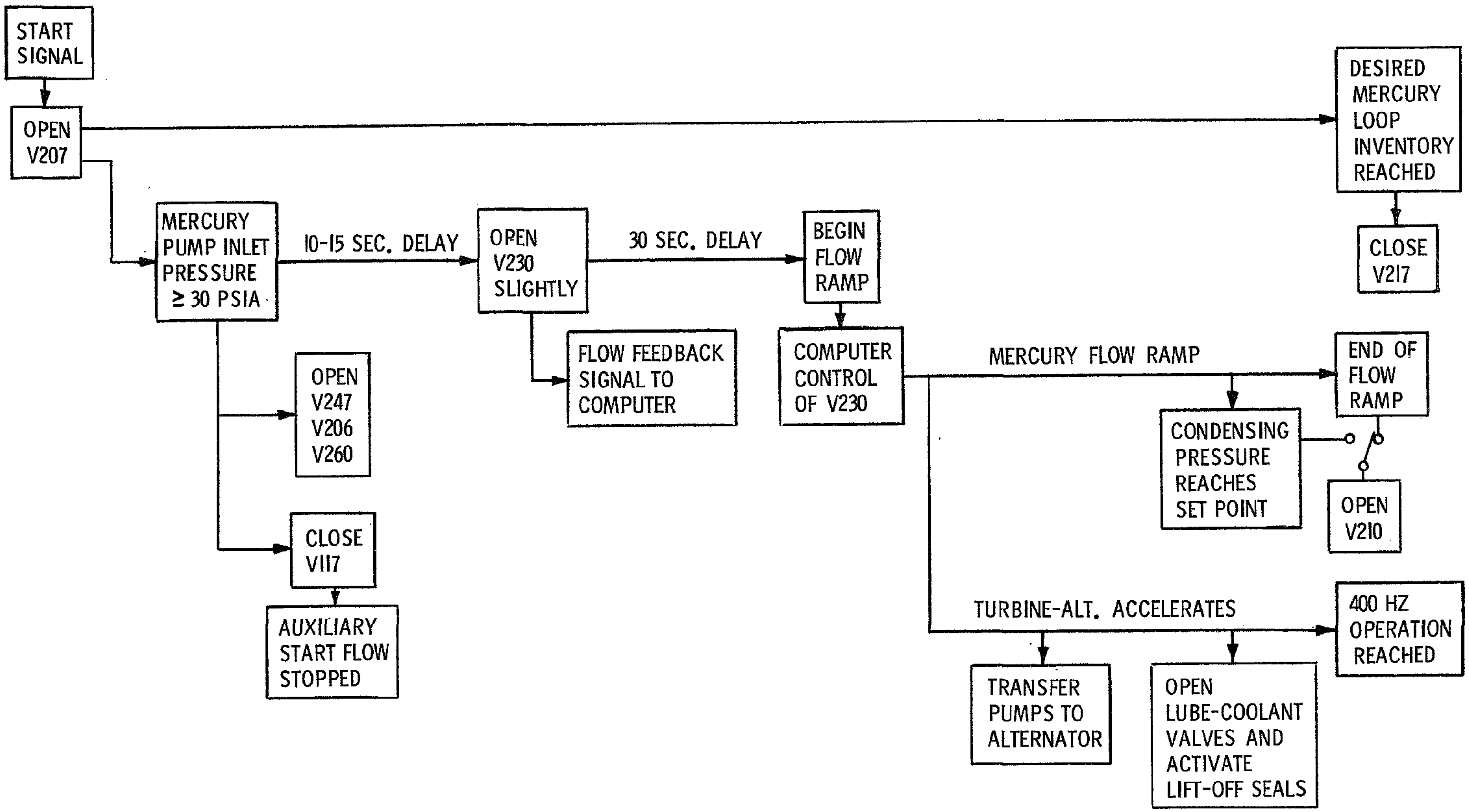

Figure 2. - Block diagram of programmer.

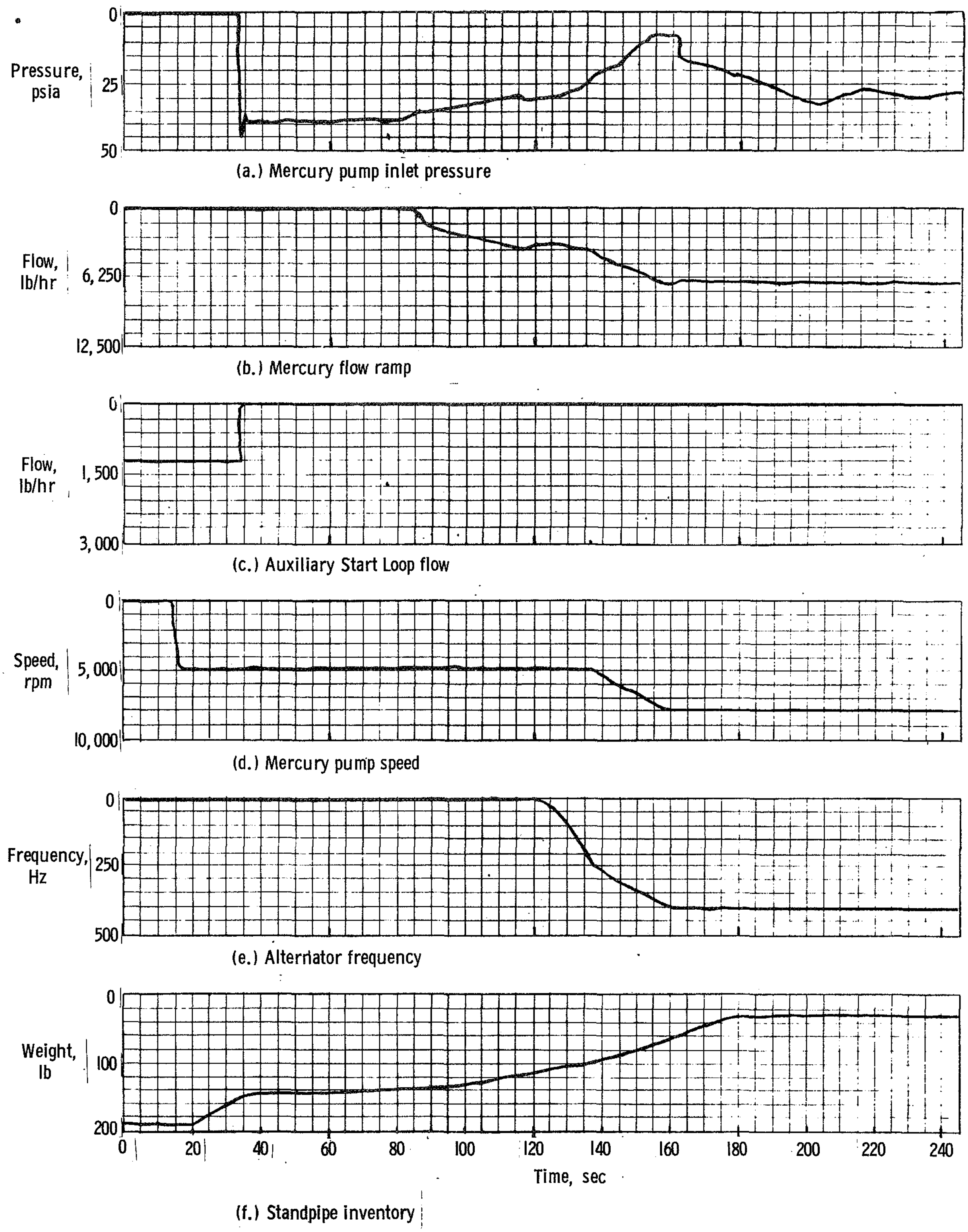

Figure 3. - Start-up performance.